GIDDINGS & PHILLIPS

No Load Losses in Dynamo Electrical Machines

Electrical Engineering

B. S.

1912

NO LOAD LOSSES IN DYNAMO ELECTRICAL MACHINES

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THESIS

FOR THE

DEGREE OF BACHELOR OF SCIENCE

IN

ELECTRICAL ENGINEERING

COLLEGE OF ENGINEERING

UNIVERSITY OF ILLINOIS

1912

UNIVERSITY OF ILLINOIS

May 28, 1902

THIS IS TO CERTIFY THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

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ENTITLED NO LOAD LOSSES IN DYNAMO ELECTRICAL MACHINES

IS APPROVED BY ME AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE

DEGREE OF BACHELOR OF SCIENCE IN ELECTRICAL ENGINEERING

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TABLE OF CONTENTS.

Page.

I. Introduction.... 2

II. Description of Losses............................ 3

III. Determination of Losses......... 7

IV. Description of Apparatus........................ 12

V. Application of Test Methods....................... 14

VI. Comparisons.. 21

VII. Conclusions............................ 22

NO LOAD LOSSES OF DYNAMO ELECTRICAL MACHINES.

I. INTRODUCTION.

In the operation of a dynamo electrical machine internal losses are encountered which reduce its efficiency. These losses vary with the size and construction of the machine, and with the speed at which it is to run. They vary, further, with the type of machine; that is, whether direct current or alternating current, etc.

The total loss is generally made up of three parts; the stray power or that which can not readily be computed from the simple data, the I^2R loss, and the load loss. The load loss may be defined as the difference between the total losses, when under load, and the sum of the stray power and I^2R losses. In commutating machines with small field distortion, the load losses are usualy very small.

The purpose of this thesis is to study the no load losses in direct current generators and motors, to investigate several of the methods of determining them, and to decide upon the relative value of the methods chosen for experimental work. The adaptability of a method as to simplicity of apparatus used, economy of power and time, and accuracy of results, is an important factor in its value as a means for measuring the losses, and is carefully considered. Because the load losses are not a part of the losses when there is no load upon the machine they will be neglected in this paper.

II. DESCRIPTION OF LOSSES.

The losses of an electrical machine are of several kinds but may be subdivided into two classes, mechanical and electrical. The mechanical losses may again be divided into two classes, those due to friction and those due to windage. The electrical losses may also be subdivided further into those due to the flow of current and those due to the magnetic fields set up by the current.

Friction Loss.

Friction is the resistance offered to the relative motion of two surfaces in direct contact. Expressed algebraically

$$F = uP$$

where F is the force required to maintain the motion, P is the pressure between the surfaces and u is the coefficient of kinetic friction. Since the friction loss is directly proportional to the pressure, it is important to have the rotating parts well balanced and properly aligned in their bearings, in order that the loss be reduced to a minimum. The value of u depends on the nature of the surfaces, but is independant of the speed so long as the speed is not "just above standstill." A part of the frictional loss is that due to friction of the brushes on the commutator. Theoretically this loss can be calculated from the following equation:

$$P = \frac{2\ f\ a\ R.P.M.\ u\ 766}{33000}$$

where P is the loss in watts, f is the brush pressure per square inch, a is the total brush area in square inches, R.P.M. is the revolutions per minute, u is the coefficient of friction

for carbon on copper, the value of which is usually given as three-tenths.

Windage Loss.

Windage is realy one form of frictional loss, being the resistance offered to rotation by the surrounding air. Theoretically it varies as the cube of the speed. Its magnitude will depend on the construction of the rotating part of the machine and upon the amount of air set in motion. In most machines therefore, the rotating part is compact and the amount of air set in motion is not given a high velocity.

Iron Losses.

When a piece of iron is magnetized it tends to retain its magnetism. This tendency causes a divergence of the curve between the flux density and the magnetizing force, for increasing values of the force, from that for decreasing values of the force. In the case of a rotating armature, or in iron where there is a periodic reversal of flux in magnitude and direction, a part of the power expended in magnetizing the iron, demagnetizing it, magnetizing it in the opposite direction, and bringing it back to the positive maximum, can not be regained. The amount of power so lost is known as the hysteresis loss of the iron. Within certain limits this may be represented by the equation:

$$W = b\ V\ B^{1.6}$$

where W is the loss of energy in ergs per cycle, b the hysteretic coefficient of the material used, V the volume of the material, and B the range of the flux density. The total loss would then be:

$$P_h = bfVB^{1.6}$$

where P_h is the loss in watts and f is the number of magnetic cycles per second, or the frequency.

A flux variation in a piece of iron tends to set up an E.M.F. in the iron, much the same as the E.M.F. would be induced in a conductor which is cutting through a field. Due to this E.M.F. currents will flow through the iron in a direction at right angles to the field flux. These currents called eddy currents, tend only to heat up the machine and it is therefore desireable to reduce them to a minimum.

To prevent the eddy currents as much as possible the iron is laminated or built up of thin sheets of metal so as to have the metal continuous in the direction of flux , but discontinuous in the direction at right angles to the flux. The eddy current loss is proportional to the volume of the iron, to the square of the number of magnetic cycles, to the square of the thickness of laminations, and to the square of the maximum flux density, or

$$P_e = aVf^2 l^2 B^2$$

where P_e is the eddy current loss in watts.

The hysteresis and eddy current losses are not usually separated when making an efficiency test upon a machine, but are considered one loss. There is also a slight loss due to hysteresis and eddy currents in the field pole pieces but this is so small that it is negligible.

Copper Losses.

The loss of power in the field windings appears as heat. It depends upon the current flowing in the field circuit and upon the resistance of the field winding, as shown by the

algebraic expression:

$$P = I^2R$$

where P is the power lost, I is the current flowing and R is the resistance of the field. However the resistance of the field varies with the temperature and if accurate results are to be obtained, correction should be made for this condition. If the temperature is taken and the temperature coefficient of copper is known, the true resistance may be computed by the following equation:

$$R_t = R_o(1 + .0042t)$$

where R_t is the resistance at the temperature t°C, R_o is the resistance at a standard temperature 0°C., and .0042 is the temperature coefficient for commercial copper.

Brush Contact Loss.

The heat loss due to the passage of current between the brushes and the commutator bars is known as the brush contact loss. Empirically it is equal to two volts drop per pair of brushes times the current at normal load. It is evident, then that at no load this loss will be negligible.

III. DETERMINATION OF LOSSES.

There are several methods for determining the losses of electrical machines. In general these are the opposition, the stray power, and the retardation methods. The opposition method may be performed in a number of different ways, which have the same underlying principles.

Opposition Method.

The main principle of this method is to drive to like machines in opposition, like machines being used in order to have the losses as nearly equal as possible. These machines are connected both electrically and mechanically, so that power is supplied from the generator to the motor electrically and from the motor to the generator mechanically.The power for the losses is supplied from a separate outside source. However, this method would be unsatisfactory in determining the no load losses.

Stray Power Method.

This method is the most common and probably the most economical since it is performed in a very short time. It consists of running the machine as a motor, under no load, and measuring the power input.

The losses within a machine are of two kinds.

(1) Losses that vary as the square of the current.

(2) losses that are constant.

The losses that vary as the square of the current are those due to the resistance of the armature and field, and the brush contact. A generator requires an excitation slightly

greater than that for a motor running at the same speed consequently increasing the field resistance loss of a generator by a small value. The total I^2R loss will be practicallyconstant for any one speed.

Having obtained the resistance by ohms law and knowing the current flowing in the respective parts of the machine for any speed the I^2R loss for each part may be computed. However, the armature loss is so small,at no load, that it may be neglected without affecting the accuracy of the test.

The constant losses are the stray power losses. These are grouped in one and include the mechanical losses (windage and friction of brushes and bearings,) and the magnetic losses due to hysteresis and eddy currents.

The stray power losses may be seperated by means of the small motor method as later described.

The friction and windage component may also be determined by running the motor at normal speed with different impressed voltages. If the motor could run at zero voltage the only loss would be that due to friction and windage. A curve plotted between the impressed volts and watts consumed by the armature will cut the axis of watts at a point that is equal to the friction and windage loss

Small Motor Method.

In this method the machine under test should be driven by a small rated motor. A rated motor is one whose efficiency is known. The normal output of the small motor would be about equal to the losses of the machine under test.

The machine should first be driven unexcited at normal speed. The power absorbed is consumed in friction of air,

bearings and brushes, and windage. The difference between the power absorbed by the small motor when driving the machine under test, and that absorbed when disconnected from this machine will be the friction and windage of the larger machine. Likewise, the brush friction loss will be the difference between the power absorbed with the brushes on and that with the brushes removed from the commutator.

The stray power loss may be determined in the same manner. It will be the difference between the power required to drive the machine with the field unexcited and that with the field normaly excited.

Retardation Method.

In some calculation of electrical machines, such as the retardation method for finding the losses, it is important to know the moment of inertia of the rotating part. This constant is difficult to calculate from the dimensions of the machine which, in turn, are difficult to measure if the machine is assembled. However, the following experimental method may be used for its determination.

The machine should first be started as a motor and run at a speed somewhat above normal and then the driving force removed. The effect of the internal losses will be to exert a retarding couple on the moving part causing it to slow down. Let the motor slow down from an angular velocity of w radians per second to an angular velocity of w_1, in (t) seconds. If $\frac{dw}{dt}$ be the rate of change of angular velocity during this period and K be the moment of inertia of the moving part, then

$$K \frac{dw}{dt} = \text{the retarding couple.}$$

In order to determine K a known retarding couple

should be applied by means of a prony or other friction brake. Let F represent this retarding couple in C.G.S. units and let $\frac{dw}{dt}_1$ be the new rate of change at the same speed. Then:

$$F = K\left[\left(\frac{dw}{dt}\right)_1 - \frac{dw}{dt}\right]$$

whence,

$$K = \frac{F}{\left[\left(\frac{dw}{dt}\right)_1 - \frac{dw}{dt}\right]}$$

English units may be used as well as C.G.S. units. In either case K will be determined in the same units in which F is measured.

The moment of inertia may also be calculated in another manner. The armature should be suspended from the end of its shaft to a rod firmly fastened at one end. The armature should then be started to vibrating about the same axis about which it rotates and the period of vibration determined.

The armature should then be replaced by a disc or other regularly shaped body such as a rectangular bar and its period of vibration determined. The moment of inertia of the disc may be readily calculated mathematically. The period of vibration of any body suspended from this rod is given by the equation:

$$T = 2\pi\sqrt{\frac{I\,l}{r}}$$

Where T is the period of vibration, I is the moment of inertia l is the length of the rod, and r is the constant of torsion of the rod. Knowing the two periods of vibration and the moment of inertia of the one body the moment of inertia of the armature may be found from the following relation:

$$\frac{K}{K_1} = \frac{T^2}{T_1^2}$$

As before let $\frac{dw}{dt}$ be the time rate of change of the velocity of the armature with the fields unexcited. Then K $\frac{dw}{dt}$ will be the retarding couple and the watts lost in friction and windage at velocity w will be:

$$Kw \frac{dw}{dt} \times 10^{-7} = \text{Watts lost.}$$

If $\left(\frac{dw}{dt}\right)_2$ be the negative acceleration when the field current is flowing then the loss due to hysteresis and eddy currents will be,

$$Kw \left[\left(\frac{dw}{dt}\right)_2 - \frac{dw}{dt}\right].$$

IV. DESCRIPTION OF APPARATUS.

Stray Power Method.

The instruments used inconnection with the stray power test for the no load losses are well known. Such instruments were an ammeter, voltmeter. and a speed counter. The ammeter and the voltmeter were of the Weston Dynamometer type, while the speed counter was of the friction type with revolving dial.

Small Motor Test.

A small four pole, shunt wound, direct current motor with a rating of one horsepower, 230 volts, and 2700 revolutions per minute was used in this test. This motor was belted to the machine to be tested and the losses of the machine determined by the power delivered from the motor.

Retardation Method.

In determining the moment of inertia of the armature a rod about twenty inches long and about three-sixteenths of an inch in diameter was used, the rod being clamped, at one end, in a vertical position. The armature was then removed from its bearings and one end of its shaft firmly fastened to the free end of the rod. The combination was thus used as a torsion pendulum.

The periods of vibration for the armature, when suspended from the rod, and that for the cast iron disc which was about sixteen inches in diameter and weighing about fifty pounds, when suspended from the same rod, were determined. From this data the moment of inertia of the armature was calculated.

In order to determine the negative acceleration of

the armature a pendulum was constructed. This pendulum was fitted with a contact maker so as to make a contact every second. In connection with this a recording apparatus consisting of two electromagnets, each operating a pen was used. One of these pens registered the time in seconds while the other registered the revolutions made by the armature. From the records made by the pens the revolutions per second for any time may be determined. From a curve between the revolutions per second and the time in seconds the negative acceleration for the time, when running at desired speed, may be calculated.

A frequency meter could also have been used to determine the negative acceleration of the armature. However, this would have involved a rather complicated apparatus in the form of a commutating device making it impractical except where a large number of tests are to be made.

V. APPLICATION OF TEST METHODS.

In order to obtain data for a comparison of the several methods of determination of losses, a Triumph Direct Current generator was selected upon which to make the investigation. The normal rating of this machine being 7.5 K.W., 120 volts and 1200 revolutions per minute. The brush pressure of this machine was about double the value of that of the ordinary machine. The field resistance was calculated by Ohm's Law and found to be 50.6 ohms.

Results of the Stray Power Test.

The data taken in the stray power test and the results as calculated appear below. In all the data obtained from observations, a mean of several readings was used.

Normal Voltage	120 Volts
Normal No Load Armature Current.	3.96 Amperes
Input in Watts, EI	475
Normal Field Resistance	50.6 Ohms
Normal No Load Field Current	2 Amperes
Field Loss in Watts	202.4 Watts
Total Loss in Watts	677.4

The stray power loss is the above input in watts minus the armature I^2R. However, the armature I^2R is less than a watt and may be neglected without materially affecting the stray power loss.

Retardation Method.

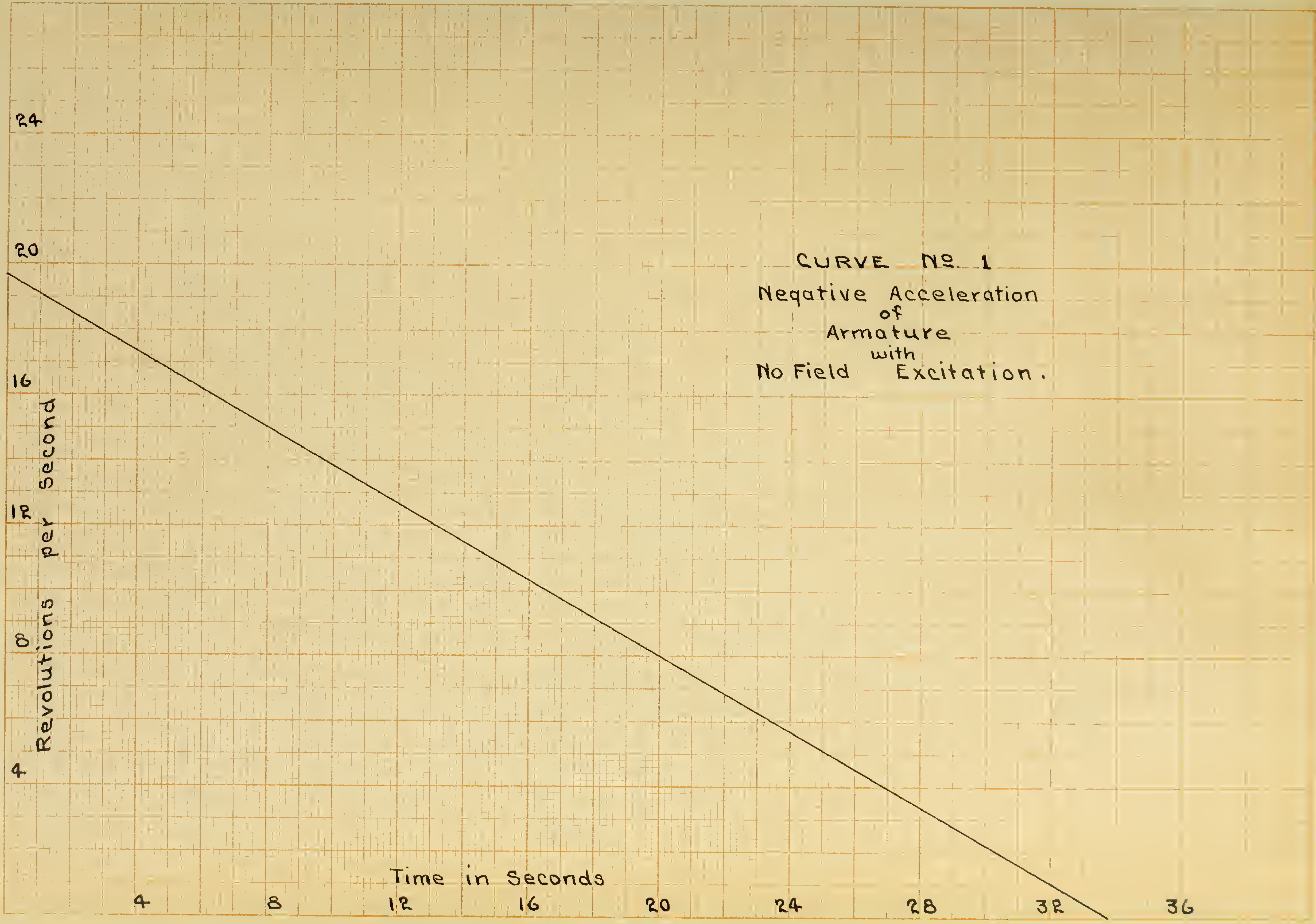
By means of the apparatus described in the preceeding pages, data for the determination of the negative acceleration was obtained, each value being the mean of four independent determinations. The field was unexcited so that the retarding

force was that due to friction and windage. From this data a curve was plotted using time as abscissae and revolutions per second as ordinates, which curve was found to be a straight line. (Curve No.1.) From this curve the angular acceleration can be found.

Table # 1.

Revolutions Per Second.	Time in Seconds.
19.09	1
18.25	3
17.00	5
15.63	7
14.50	9
13.57	11
12.12	13
11.05	15
10.03	17
8.36	19
7.23	21
6.13	23
4.95	25
3.04	27
2.96	29

The data shown in Table No. 2 was taken for the retardation of the armature with the field normally excited.


CURVE No. 1
Negative Acceleration
of
Armature
with
No Field Excitation.
Revolutions per Second
24
20
16
12
8
4
Time in Seconds
4
8
12
16
20
24
28
32
36

As before each reading in the following table is the mean of several observations.

Table # 2.

Revolutions Per Second.	Time in Seconds.
18.70	1
16.47	3
14.28	5
11.76	7
9.29	9
6.85	11
4.43	13
1.98	15

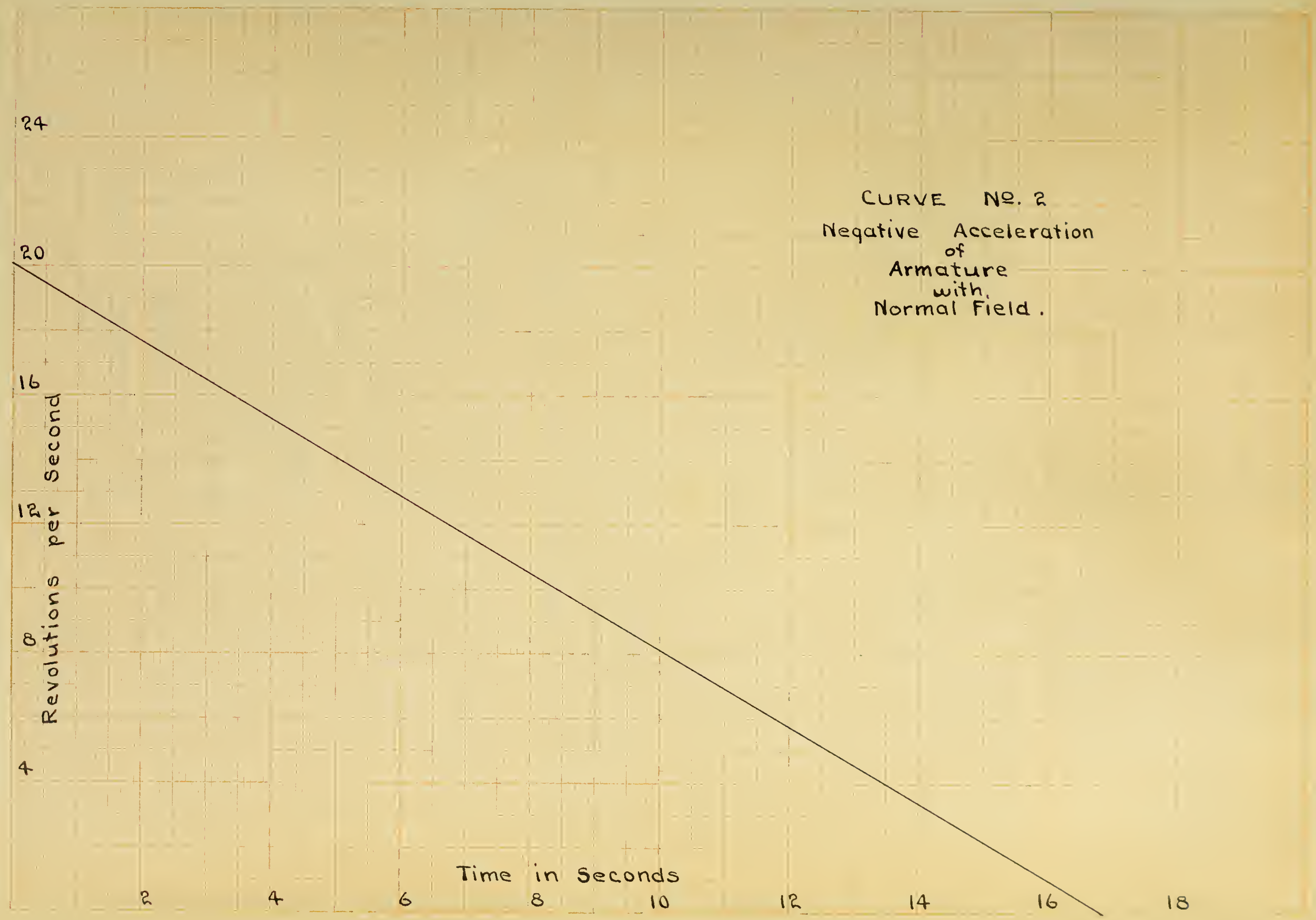
Again a curve was plotted using time in seconds as abscissae and revolutions per second as ordinates, from which curve the negative acceleration $\left(\frac{dw}{dt}\right)_2$ can be computed. (Curve #2)

Determination of the Moment of Inertia

In order to determine the moment of inertia of the armature the period of vibration of the armature as a torsion pendulum was compared to the period of vibration of a disc whose moment of inertia could be computed from measurements. A number of observations were taken from which the mean in each case is here given.

	No. of Swings.	Time in Seconds.	Period of Oscillation.
Armature	100	131.00	1.31
Disc	100	119.8	1.198

From this data the following calculations were made and


CURVE No. 2
Negative Acceleration
of
Armature
with
Normal Field.
Revolutions per Second
24
20
16
12
8
4
Time in Seconds
2
4
6
8
10
12
14
16
18

the moment of inertia of the armature was determined.

Weight of Disc .	23027.6 grams
Mass of Disc	23027.6 grams
Diameter of Disc.	40.8 cm.
Radius of Disc	20.4 cm.
Moment of Inertia of the Disc $\frac{1}{2}MR^2$	4789242.
Period of Disc T_1	1.198 seconds
Period of Armature T_2	1.31 seconds

I_1 is the moment of inertia of the disc, and I_2 is the moment of inertia of the armature.

Also. $I_1 : I_2 :: T_1^2 : T_2^2$

Moment of Inertia of the Armature.

$$I_2 = I_1 \frac{T_1^2}{T_2^2} = 5720211$$

Determination of Frictional Losses.

From curve No. 1 the negative acceleration, $\frac{dw}{dt}$ is found to be .58. The retarding couple or frictional force is given by

$$F = Ia$$

where a is the angular acceleration expressed in radians per second per second. Then the moment of force will be

$$5720211 \times .58 \times 2 \times 3.1416 \times 10^{-7} = 2.07$$

The loss in watts will be

$$2.07 \times 2 \times 3.1416 \times \frac{1200}{60} = 258$$

which is the windage and friction plus a brush loss.

From curve No.2 the negative acceleration with normal field excitation, $\left(\frac{dw}{dt}\right)_2$ is 1.19. Then as before the moment of force or retarding couple will be:

$$5720211 \times 1.19 \times 2\ 3.1416 \times 10^{-7} = 4.27$$

The lossin watts will be:

$$4.27 \times 2 \times 3.1416 \times \frac{1200}{60} = 538$$

The core loss equals 538- 258 = 280 watts.

The brush loss may be calculated if the pressure of brushes on the commutator, coefficient of friction of carbon and copper, and the normal speed are considered.

The total losses by this method are then:

Windage and friction plus brush losses	258 watts
Core loss	280 watts
Field I^2R loss	202 watts
Total No Load Losses	740 watts.

Determination of Losses with Small Motor.

In the test with the small motor the rating of that motor must first be determined. The following is the mean of several observations for the determination of the loss in this motor when disconnected from the larger machine.

Volts Impressed	Current	Watts Lost EI
218	1.21	264

The belt loss was assumed to be two percent of the rating of the small motor, or fifteen watts. The total losses external to the machine to be tested are then:

264 — 15 = 279 watts.

The following observations werethen taken to determine the loss due to brush friction on the commutator.

Brushes On.			Brushes Off.		
E.M.F.	I	Watts Consumed by Small Motor.	E.M.F.	I	Watts Consumed by Small Motor.
216.3	2.61	565	216.6	1.725	373

The brush friction loss is then:

505 - 373 = 192 watts.

while the friction and windage of armature and bearings is:

373 - 279 = 94 watts.

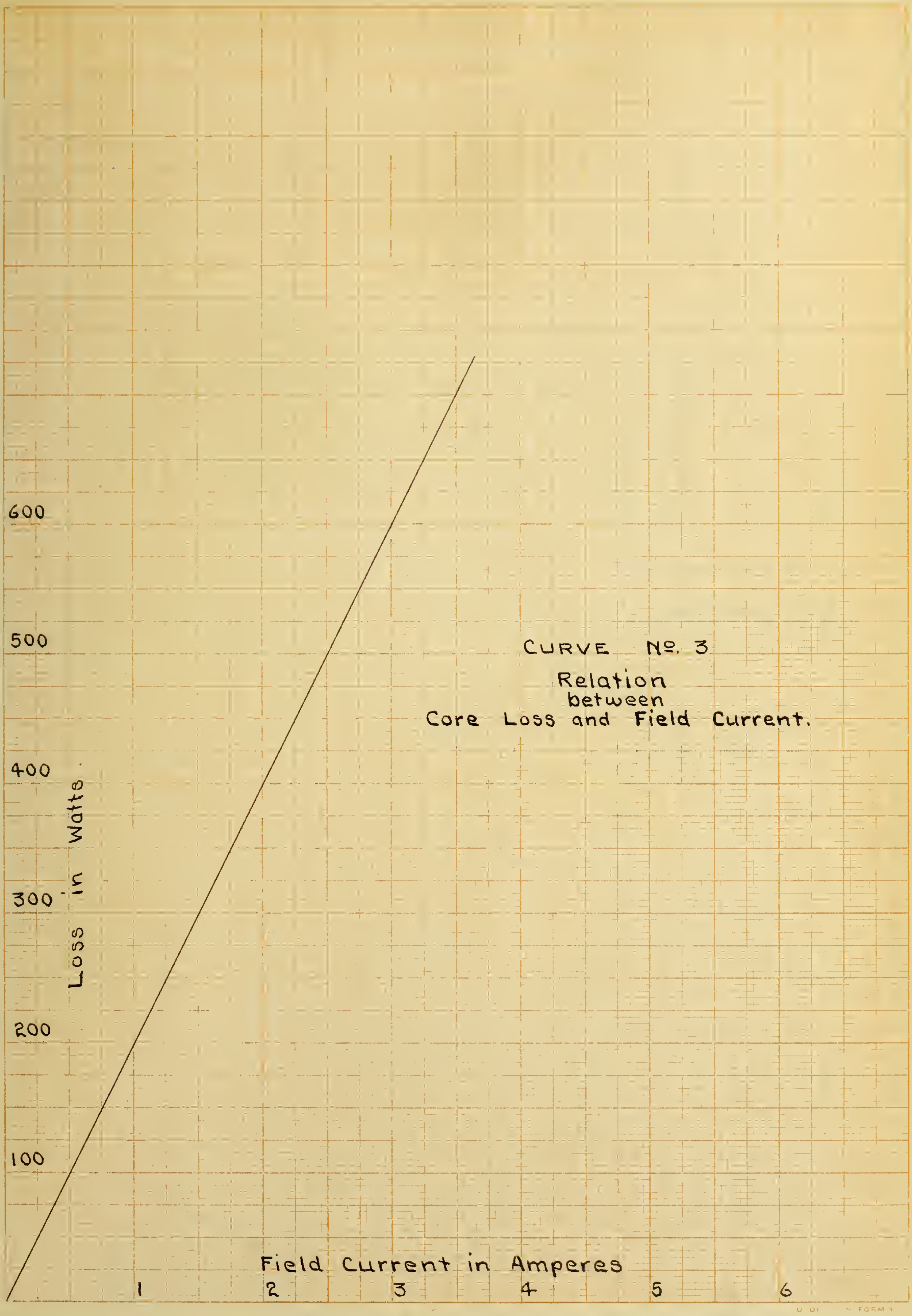
The following is a table of mean observations to determine the core loss of the machine under test when running at normal speed with different field excitations.

Table # 3.

Field Current Amperes	Speed R.P.M.	E.M.F. on Small Motor.	I in Motor Armature	Watts Consumed by Motor.	Motor Rating* Plus Belt Loss	Core Loss Watts.
0.500	1200	215.80	1.9050	411	279	132
1.000	1200	214.85	2.2600	484	279	205
1.500	1200	214.25	2.7400	588	279	309
2.025	1200	216.25	3.2625	708	279	429
2.500	1200	215.56	3.6350	784	279	505
2.775	1200	217.32	3.9000	849	279	570
3.025	1200	216.00	4.0000	865	279	586

A curve (curve #3) was plotted between core loss and the field current. From this curve the core loss for the normal field current of two amperes was found to be 400 watts.

* Motor rating is the power consumed by the small motor when running under no load.



CURVE No. 3
Relation
between
Core Loss and Field Current.
Loss in Watts
600
500
400
300
200
100
Field Current in Amperes
1
2
3
4
5
6

The total No Load Losses as measured with the small motor are, then:

Brush Loss	192 watts
Friction and Windage Loss	94 watts
Core Loss	400 watts
Field I^2R Loss	202 watts
Total No Load Losses	888 watts

It is interesting to note that the curve between core loss and field current is a straight line for this particular machine. Ingeneral the curve between the flux and the field current is concave downward, while that between the core loss and flux is concave upward. In this case, however, the deviation of the flux-current curve from a straight line just offsets that of the core-loss-flux curve causing the core loss-current curve to be a straight line.

VI. COMPARISONS.

A comparison of the results obtained in the tests under the three methods taken up and discussed shows that there is some range of variation. Greater attention has been paid to the retardation method; while the small motor and the stray power tests were used more as a check on the results obtained in the retardation method test. There was a smaller range of variation in the determination of the mean readings with the retardation method than with the other methods, therefore, more confidence can be placed upon the results as obtained with this method.

A comparison of the three methods can well be shown as follows:

Stray Power Method, Total No Load Loss	677 watts
Retardation Method, Total No Load Loss	740 watts
Small Motor Method, Total No Load Loss	888 watts

The retardation method gives a loss which is approximately the mean of the losses by the other two methods.

VII. CONCLUSIONS.

In determining the no load losses in any machine the importance to be attached to the results will determine the method to be used.

When accurate data is desired the retardation method is the best. It will, however, require more apparatus, and in most cases more time than either of the other methods. Where the necessary apparatus is at hand this method can be used with as great economy of time as any other.

It might seem that it would be a difficult task to calculate the moment of inertia of the armature in the case of a very large machine. If the armature be to large to remove from its bearings and handle expediently, the negative acceleration - hence the moment of inertia -,can be found by letting the armature come to rest from some given speed.

When it is desirable to run a test with a minimum power consumption, the stray power method is best. For ordinary purposes it will be found to be of sufficient accuracy to be practical.

The small lotor method is one very well adapted to machines of medium or large size. It is a good method in any case where very accurate results are not essential although it compares well with the stray power method in this respect. When it is used the various losses can be seperated more readily than would be possible in the stray power or other methods.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